Multi-objective optimization and evaluation of supercritical CO2 Brayton cycle for nuclear power generation

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Abstract

The supercritical CO2 Brayton cycle is considered a promising energy conversion system for Generation IV reactors due to its simple layout, compact structure, and high cycle efficiency. In this study, mathematical models of four Brayton cycle layouts are developed for different reactors to reduce costs and enhance the thermohydraulic performance of nuclear power generation, thereby promoting the commercialization of nuclear energy. Parametric analysis, multi-objective optimization, and four decision-making methods are applied to obtain the optimal thermohydraulic and economic indicators for each Brayton scheme. The results show that for reactors with the same design thermal power scale, the higher the core outlet temperature, the better the thermo-economic performance of the Brayton cycle. Among the four cycle layouts, the recompression cycle (RC) exhibits the best overall performance, followed by the simple recuperation cycle (SR) and the intercooling cycle (IC), while the re-heating cycle (RH) performs the worst. However, RH has the lowest total investment cost (Ctot) of 1619.85$million, andIChasthelowestlevelizedcostofenergy(LCOE)of$0.012/(kWh). The overall performance of the nuclear Brayton cycle system has been improved through optimization. The Molten Salt Reactor combined with the intercooling cycle (MSR-IC) scheme shows the greatest improvement in performance, with net output power (Wnet), thermal efficiency t, and exergy efficiency (e) increasing by 8.58%, 8.58%, and 11.21%, respectively. The performance of the Lead-cooled Fast Reactor combined with the simple recuperation cycle scheme was optimized, resulting in a 27.78% increase in Ctot. In contrast, the internal rate of return (IRR) increased by only 7.8%, which is unfavorable for investors with limited capital. For nuclear Brayton cycles, the Molten Salt Reactor combined with the recompression cycle scheme should be given priority, while the Gas-cooled Fast Reactor combined with the re-heating cycle scheme should be considered with caution.

Full Text

Multi-Objective Optimization and Evaluation of Supercritical CO_2 Brayton Cycle for Nuclear Power Generation

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Abstract

The supercritical CO_2 Brayton cycle (S-CO_2BC) is considered a promising energy conversion system for Generation IV reactors due to its simple layout, compact structure, and high cycle efficiency. This study develops mathematical models of four Brayton cycle layouts for different reactor types to reduce costs and enhance the thermohydraulic performance of nuclear power generation. Multi-objective optimizations are performed, and four decision-making methods are applied to obtain the optimal thermohydraulic and economic indices for each Brayton scheme.

Results show that for reactors with the same design thermal power scale, higher core exit temperatures yield better thermo-economic performance of the Brayton cycle. Among the four cycle layouts, the recompression cycle (RC) demonstrates the best overall performance, followed by the simple recuperation cycle (SR) and the intercooling cycle (IC), while the re-heating cycle (RH) performs worst. However, RH exhibits the lowest total investment cost (Ctot) of $1619.85 million, and IC has the lowest levelized cost of energy (LCOE) of 0.012/$(kWh). Optimization improves the overall performance of the nuclear Brayton cycle system. The Molten Salt Reactor combined with the intercooling cycle (MSR-IC) shows the greatest improvement, with net output power (Wnet), thermal efficiency (t), and exergy efficiency (e) increasing by 8.58%, 8.58%, and 11.21%, respectively. In contrast, the Lead-cooled Fast Reactor combined with the simple recuperation cycle (LFR-SR) optimization increases Ctot by 27.78% while the internal rate of return (IRR) increases by only 7.8%, which is unfavorable for investors with limited funds.

For nuclear Brayton cycles, the Molten Salt Reactor combined with the recompression cycle (MSR-RC) should be prioritized, while the Gas-cooled Fast Reactor combined with the re-heating cycle (GFR-RH) should be considered carefully.

Keywords: Supercritical CO_2 Brayton cycle; Nuclear power generation; Thermo-economic analysis; Multi-objective optimization; Decision-making methods

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Nomenclature

Symbols
A – area, m^2
C – heat capacity, J/K
c – cost, $
D – flow channel diameter, m
Dh – hydraulic diameter, m
f – friction coefficient
h – specific enthalpy, kJ/kg
I – exergy destruction, W
L – channel length, m
$\dot{m}$ – mass flow rate, kg/s
p – pitch, mm
P – pressure, kPa
PR – pressure ratio
Q – heat energy, W
s – specific entropy, kJ/(kg · K)
t – thickness, mm
T – temperature, K
V – volume flow, m^{2}/s
W – work, kJ

Subscripts
0 – ambient conditions
c – cold fluid
h – hot fluid
e – exergy
k – work fluid state point
in – inlet
min – minimum
max – maximum
out – outlet
tot – total
rev – revenues

Acronyms
GFR – Gas-cooled Fast Reactor
SFR – Sodium-cooled Fast Reactor
LFR – Lead-cooled Fast Reactor
MSR – Molten Salt Reactor

SR – Simple recuperation cycle
RC – Recompression cycle
RH – Re-heating cycle
IC – Intercooling cycle
SC – Specific cost
LCOE – Levelized cost of energy
IRR – Internal Rate of Return
PBP – Payback period
SP – Size parameters
APR – Area per net output power
HX – Heat exchanger
HTR – High temperature recuperator
LTR – Low temperature recuperator
MC – Main compressor
DMM – Decision-making method
NSGA-II – Non-dominated sorting genetic algorithm
ORC – Organic Rankine cycle
PC – Pre-cooler
R – Recompressor
T – Turbine
S-CO_{2}BC – Supercritical carbon dioxide Brayton cycle

Greek letters
– surface roughness
– efficiency
– kinematic viscosity
– relative roughness
– density
– heat transfer coefficient

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1. Introduction

The overuse of fossil energy is one of the major causes of global warming [1]. As one of the most efficient and clean energy sources, nuclear energy has been criticized for its high investment costs [2] and safety concerns [3]. However, scholars have continued researching nuclear energy, and with the introduction of fourth-generation nuclear reactors, nuclear power generation has gradually become a research hotspot [4-6]. Most current power conversion systems in power plants use steam Rankine cycles and gas turbine systems, but high reactor outlet temperatures and pressures limit the efficiency of nuclear power conversion systems [7].

Compared with the steam Rankine cycle [8], the supercritical carbon dioxide (S-CO_{2}) power cycle offers higher system thermal efficiency and more compact power system equipment [9], making it well-suited for nuclear power applications. While supercritical helium power cycles offer advantages in ultra-high temperature systems (above 1000°C), S-CO_{2} power cycles are more suitable for medium-temperature operation (450-600°C) in Generation IV reactors [10]. Its simple layout and compact structure can reduce investment costs for nuclear power generation systems, providing economic advantages over other energy types [11]. Additionally, the small footprint allows high-power-density nuclear equipment to be factory-assembled and transported to construction sites by truck or train [12], facilitating commercial deployment.

Current research on S-CO_{2}BC has focused on system performance optimization [13], working fluid selection [14], techno-economic features, and integration with other thermal energy systems [15-17]. Ahn et al. [7] conducted comparative analyses of S-CO_{2}BC systems under various cycle layouts and found that recompressed Brayton cycle systems achieve higher thermal efficiency and emergency efficiency than other configurations. Kim et al. [18] analyzed parameters such as thermal efficiency and net output power for an S-CO_{2} recompressed Brayton cycle using the pinch-point temperature difference method, optimizing operating conditions for heat exchangers and other components. Song et al. [19] investigated combined S-CO_{2} Brayton and organic Rankine cycles (ORC), optimizing operating parameters to significantly improve the combined cycle's thermal performance. Bian et al. [20] evaluated the effects of different control valves on the dynamic performance of S-CO_{2}BC systems from thermodynamic and safety perspectives. Wang et al. [21] studied dynamic response characteristics under S-CO_{2} Brayton cycle failure conditions and proposed contingency measures.

While these studies on S-CO_{2} cycle systems employed single objective functions for evaluation, such approaches cannot fully reflect the performance characteristics of S-CO_{2} cycle systems. Consequently, many scholars have established multi-objective functions to investigate key evaluation parameters including thermal efficiency, net output power, and irreversible energy loss. Wang et al. [22] developed multi-objective functions using system thermal efficiency and net output power as evaluation parameters for S-CO_{2}BC applications in tower solar power systems, optimizing various cycle configurations including simple recuperation, recompression, and pre-compression cycles. Battisti et al. [23] used system thermal efficiency and heat transfer coefficient as objective functions in S-CO_{2}BC to determine optimal performance based on variations in heat source temperature, working fluid mass flow rate, and maximum working fluid temperature. Nami et al. [24] conducted an exergoeconomic analysis of a combined heat and power (CHP) system incorporating a gas turbine, S-CO_{2}BC, and ORC. Mohammad et al. [25] optimized the techno-economics of a simple recuperation Brayton cycle based on the genetic algorithm (GA) so that the cycle produces 71% of the maximum power at the optimum point but at a cost rate of only 33% of the maximum power state. Li et al. [26] also considered the ecological performance of the system. They used the non-dominated sorting genetic algorithm (NSGA-II) to optimize the net output power, thermal efficiency, and ecological performance of the Brayton cycle system driven by a hybrid of fossil fuel and solar power.

In multi-objective optimization, due to the conflict between different objectives, optimizing one objective is at the cost of deteriorating other objectives, so obtaining a unique optimal solution is difficult. Instead, coordination and compromise are made among them so that the overall objective is as optimal as possible [27]. The general optimization algorithms all aim to obtain an optimal set of solutions called the Pareto frontier [28]. Many methods have been proposed for obtaining compromise solutions from the Pareto frontier. Li et al. [29] used the NSGA-II method to optimize the proposed Brayton cycle model. In addition, multi-attribute decision-making methods (MADM), such as TOPSIS, LINMAP, and Shannon entropy, were used to select the optimal system parameters from the Pareto frontier calculated by the NSGA-II method. Arora et al. [30] proposed a thermodynamic model of a simple recuperation Brayton system with irreversibility based on finite-element thermodynamic analysis. The proposed model was optimized using NSGA-II and a multi-objective evolutionary algorithm based on decomposition (MOEAD), and the proposed model was optimized by Shannon entropy, LINMAP, Fuzzy, Bellman-Zadeh, TOPSIS, and other MADM methods to find the optimal system parameters from the Pareto frontier. Rao et al. [31] proposed a new multi-objective optimization method, the Rao algorithm. A combined solar Brayton cycle-power system case study also investigated the proposed Rao algorithm. The MADM method was used to rank the Pareto optimal solutions based on the average rank. Kumar et al. [30] performed a multi-objective optimization of the Brayton cycle system model by NSGA-II, determining the optimal design parameters from the Pareto frontier using MADM methods such as Shannon entropy, LINMAP, Fuzzy, and TOPSIS.

Therefore, most of the research on multi-objective optimization of S-CO_{2}BC based on nuclear power generation has been limited to thermodynamic performance. In contrast, some research has been conducted on its economics and safety. Also, there are few effective methods for determining the unique optimal solution for multi-objective optimization. This study develops a mathematical model of the Brayton cycle for four different cycle layouts and four Generation IV nuclear reactors. NSGA- is used to optimize two objectives, t and LCOE, simultaneously. The results of the four decision methods are evaluated using Taylor diagrams to obtain the unique optimal solution. Finally, the comprehensive evaluation results of the multi-index are provided.

The main contribution of this study is as follows: A sensitivity analysis of seven key parameters for four different layouts of the Brayton cycle was carried out to determine the decision variables and their range of values. The influence of the design parameters on the thermodynamics and economics of the system was analyzed. Taylor diagrams were used to evaluate the Pareto compromise solutions determined by the four MADM methods and to determine the unique optimal solution. The G1+TOPSIS method was used to comprehensively evaluate the optimization results by comparing 16 schemes comprising four nuclear reactors and four layouts in terms of safety, compactness, thermal, and economic performances. The characteristics and final ranking of each scheme are also given. Decision-makers can make scheme choices based on demand.

2. System Layouts and Assumptions

This study uses four different layouts of the Brayton cycle for optimization. One of the most basic cycle layouts is the simple recuperation cycle (SR). It consists of a turbine (Turb), a heat exchanger (HX), a recuperator (RC), a pre-cooler (PC), a compressor, and a generator, as shown in Figure 1 [Figure 1: see original paper]. The working fluid is heated in the recuperator (state points 2 to 3) after being compressed near the critical point (state points 1 to 2) and then reheated by the cooling medium of reactor coolant in the heat exchanger (state points 3 to 4). At this point, the working fluid, which has a high enthalpy at the heat exchanger outlet, will expand in the turbine to do work and drive the generator to produce electricity (state points 4 to 5). The expanded working fluid is then cooled on the low-pressure side of the recuperator (state points 5 to 6) and further cooled by exchanging heat with cooling water in the pre-cooler before being compressed again (state points 6 to 1).

Fig. 1. (a) Schematic and (b) T-S diagram of a simple recuperation cycle (SR).

Fig. 2 [Figure 2: see original paper] shows the recompression cycle (RC), which has one more recompressor and recuperator than the simple recuperation cycle. In the recompression cycle, the working fluid is split at the outlet of the low-temperature recuperator (LTR) (state point 8), part of the fluid enters the pre-cooler (state points 2 to 3), and the rest enters the recompressor (state points 8 to 3b), finally converging at the high-pressure inlet side of the high-temperature recuperator (state point 3b). As the specific heat capacity of the fluid on the low-pressure side of the recuperator is less than that on the high-pressure side, increasing the mass flow rate of the fluid on the low-pressure side can balance the specific heat capacity on both sides of the recuperator, enhancing heat recovery and avoiding the pinch point.

Fig. 2 (a) Schematic and (b) T-S diagram of the recompression cycle (RC).

The other two-cycle layouts are the reheating cycle and the intercooling cycle. As shown in Fig. 3 [Figure 3: see original paper] and Fig. 4 [Figure 4: see original paper], the working fluid is heated and expanded twice in the reheating cycle (state points 4 to 5 and 6 to 7), which means that more expansion work (Wtur1 and Wtur2) can be produced for the same compression work input (Wc), resulting in a higher net output work and cycle efficiency. The intercooling cycle regulates the minimum pressure (P1) and intermediate pressure (P8) of the cycle using secondary compression and intercooling, thus reducing the required compression work (Wc1 and Wc2) to increase the cycle efficiency.

Several general assumptions are made to simplify the simulation, as follows:

(1) The S-CO_{2}BC operates in the steady state. (2) The heat losses are neglected during each part of the experiment. (3) The cooling water used in the cooler is in the environmental state. (4) The resistance loss of the pipeline is ignored.

Fig. 3. (a) Schematic and (b) T-S diagram of the reheating cycle (RH).

Fig. 4. (a) Schematic and (b) T-S diagram of the intercooling cycle (IC).

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3. Methodology

A comprehensive multi-index evaluation and optimization method based on designing power conversion systems for nuclear power plants can guide decision-makers. As shown in Table 5 , the method is based on the hierarchical analysis method, which consists of the scheme hierarchy (four nuclear reactors and four-cycle layouts), the index hierarchy (consisting of 11 indices at four levels), and the target hierarchy (The best scheme can be evaluated based on the actual needs of decision-makers). The data in the index hierarchy is obtained from the model layer. Before the final evaluation, it is necessary to optimize each scheme to ensure the accuracy of the evaluation.

The optimization process mainly uses the NSGA- algorithm to obtain the Pareto optimal frontier. Then, four multi-attribute decision methods are used to obtain the compromise schemes. Finally, the optimal results of each scheme were obtained by comparing the four compromise schemes through Taylor diagrams. The optimal results are evaluated to obtain the optimal scheme.

Fig. 5 [Figure 5: see original paper]. Description of comprehensive multi-index evaluation and optimization method.

3.1 Fundamental Model

This section presents the thermodynamic model, the heat exchanger thermal-hydraulic model, and the techno-economic model for the nuclear Brayton cycle system. The models are mainly constructed by calling the NIST REFPROP database through the simulation program.

3.1.1 Thermodynamic model A thermodynamic model was constructed based on the first and second principles of thermodynamics. The energy calculations for the main components for all cycle layouts are given in Table 1 . In Table 1, Q represents the heat transfer flow rate, W represents output/input power, and h represents enthalpy.

Table 1 Calculation of energy of main components.

Components	Energy
Heat exchanger	Q_{HX} = ṁ(h_{out} - h_{in})
Recuperator	Q_{Recup} = ṁ_h(h_h,in - h_h,out) = ṁ_c(h_c,out - h_c,in)
Turbine	W_{Tur} = ṁ(h_{in} - h_{out})
Compressor	W_C = ṁ(h_{out} - h_{in})

For the recompression cycle, the total input power of the main compressor and recompressor can be expressed as:

$$W_{C,total} = W_{MC} + W_{RC}$$

Where: SR is the system circulation diversion ratio.

In the reheating cycle, as shown in Fig. 3, the reactor cooling fluid is divided equally into two parts, which are heated in turn to the working fluid and then converge and enter the reactor, and the heat transfer flow rate between the two times is expressed as:

$$Q_R = \dot{m}_r c_p \Delta T_{cf}/2$$

Where: cp is the specific heat capacity of the reactor cooling fluid, and ΔTcf is the confluence temperature difference of the reactor cooling fluid.

The net output work of the S-CO_{2}BC system:

$$W_{net} = W_{tur} - W_c$$

The thermal efficiency of the S-CO_{2}BC system:

$$\eta_t = \frac{W_{net}}{Q_{in}}$$

Exergy is the part of the energy that can do work, and the exergy destruction is inevitable in the actual process. Exergy efficiency is an effective method to evaluate the supercritical Brayton cycle. The exergy of each state point can be calculated by:

$$E = \dot{m}[(h - h_0) - T_0(s - s_0)]$$

Where m denotes the working fluid mass flow rate, hi and si are the specific enthalpy and entropy at each point, and 0 refers to the environment state. TR is the temperature of the coolant that enters HX to provide heat for the cycle.

The cycle exergy efficiency is defined as:

$$\eta_e = \frac{W_{net}}{E_{in}}$$

3.1.2 Heat exchangers' thermal-hydraulic model PCHEs were chosen for the heat exchange thermal-hydraulic model because they have been adopted in many studies on SCO_{2}-based power cycles due to their compact size and ability to withstand high pressures. A model similar to that proposed in Dostal's Thesis [32] is used in this work. According to the assumptions established in the Ref.[32], it is sufficient to model a pair of hot and cold channels rather than the entire core of the PCHE. PCHEs adopt a semi-circular straight channel model [33]. Fig. 6 [Figure 6: see original paper] is the structural diagram of a heat exchange unit.

Fig. 6. Structure diagram of PCHE.

The logarithmic mean temperature difference (LMTD) method was used to calculate the heat transfer area, as indicated in Eq. (18). The total heat transfer coefficient was calculated using the contributions of the thermal resistances by conduction and convection (Eq. 19), and the convective transfer coefficient was calculated using Eq. (20), where D is the hydraulic diameter. The calculation formula is shown in Eq. (21), and the Reynolds number is calculated using Eq. (22).

$$Q = UA\Delta T_{lm}$$

$$\frac{1}{U} = \frac{1}{h_h} + R_{cond} + \frac{1}{h_c}$$

$$h = \frac{Nu \cdot k}{D_h}$$

$$Re = \frac{\rho V D_h}{\mu}$$

In the hydraulic model, only pressure drops due to friction were considered. The well-known Darcy-Weisbach equation (Eq. 25) was applied in each segment. The total pressure drop for each channel is given by Eq. (27).

$$\Delta p = f\frac{L}{D_h}\frac{\rho V^2}{2}$$

In Appendix A, the equations used to calculate the Nusselt number (Nu) and the friction factor (f) are presented. It is worth noting that in PCHE, the relative roughness of the pipe is the ratio of the surface roughness (=10^{-3} is used in this study) [32] to the pipe diameter d.

3.1.3 Model validation This study intends to establish and verify the model through simulation software based on the data of the Advanced Burner Test Reactor Preconceptual Design Report provided by Argonne National Laboratory in the United States [33]. This experiment is a performance study of the Sodium-cooled Fast Reactor coupled with the S-CO_{2} recompression Brayton cycle (RC); the reactor cooling medium is metallic sodium. The initial parameters for cycle simulation are given in Table 2 and Table 3 for validation. The comparison between the model established in this study and the experimental parameters in the references is shown in Fig. 7 [Figure 7: see original paper] and Table 4 . The errors of entropy and temperature at each point of the cycle are guaranteed to be within 3%, which verifies the model's accuracy. Therefore, further parameter analysis and the model can be used for optimization.

Table 2 Setting parameters in the experiment [33].

Parameter	Value
Turbine inlet temperature Tmax(K)	823
Main compressor inlet temperature Tmin (K)	305
Main compressor inlet pressure Pmin(MPa)	7.7
Main compressor outlet pressure Pmax(MPa)	20
Turbine isentropic efficiency T	0.93
Main compressor isentropic efficiency MC	0.89
Recompressor isentropic efficiency RC	0.89
Environment temperature T0(K)	305
Environment pressure P0(MPa)	0.101
Shunt ratio SR	0.5
Reactor power Qr(MWt)	100
Sodium mass flow mr(Kg/s)	485
Sodium inlet temperature Tr,in(K)	886
Sodium outlet temperature Tr,out(K)	823

Table 3 Geometric parameters of PCHE [33].

Parameter	Value
t(mm)	1.5
d(mm)	2
p(mm)	2.4

Table 4 Comparison between the results calculated using the established model and the data from Ref [33].

Parameters	Reference	Calculated	Error (%)
Working fluid (CO_{2}) mass flow rate mf (kg/s)	1256	1293	2.9
Compressor input power WC (KW)	23600	23900	1.3
Turbine output power WTur (KW)	45000	45900	2.0
Cooler outlet water temperature TWater,out (℃)	35	34.8	0.6
Thermal efficiency t (%)	42.7	43.2	1.2

Fig. 7. Validation of the constructed S-CO_{2}BC model.

3.1.4 Techno-economic model Four economic indices and two compactness indices have been adopted in this study to holistically assess the techno-economics of the nuclear Brayton cycle. Specifically, these include the heat transfer area per net output power (APR) and the turbine characteristic size parameter (SP), which represents compactness, and Ctot, SC, LCOE, and IRR, which represent economy.

The heat transfer area per net output power (APR), which is the ratio of heat exchange area to net output work, is used as an evaluation criterion for the compactness of the heat exchanger. APR is defined as:

$$APR = \frac{A_{HX}}{W_{net}}$$

The turbine characteristic size parameter (SP) is an index used to evaluate the ease and compactness of turbine manufacturing. The smaller the SP, the more compact the turbine structure. It is defined as:

$$SP = \frac{\sqrt{V_{Tur}}}{\Delta h_{isen}^{0.25}}$$

Where VTur denotes the volume flow rate of the working fluid in the turbine, Δhisen denotes the isentropic enthalpy drop at the inlet and outlet of the working fluid of the turbine.

The specific cost (SC) represents the average investment cost of the unit power output of the power plant and is defined as:

$$SC = \frac{C_{tot}}{W_{net}}$$

The cost of PCHE is calculated by referring to the calculation method in Dr Dostal and the quotation of Heatric (30 $/kg) [32], with PCHE weight calculated to estimate costs. The PCHE volume (VPCHE) and actual volume per cubic meter (fm) are used in weight calculations.

$$C_{PCHE} = m_{PCHE} \times 30\$/kg$$

3.2 Multi-Objective Optimization Framework

No single reactor type and cycle layout can simultaneously achieve optimal techno-economic and thermodynamic performance, so selection depends on specific requirements. The ideal point on the Pareto frontier diagram lies in the lower right corner outside the rectangular frontier, representing the theoretical goal of maximizing t while minimizing LCOE. To determine Pareto compromise solutions, this study applies four decision-making methods—Shannon entropy, modified TOPSIS, LINMAP, and AHP—and compares them using Taylor diagrams. These diagrams determine the final Pareto optimal solution by measuring root-mean-square difference, correlation coefficient, and standard deviation.

Figure 16 shows the positions of optimal solutions determined by different decision methods on the Pareto frontier. The Shannon entropy point is located at the maximum t point at the frontier's top, while the LINMAP point lies in the middle. The TOPSIS and AHP points are close to the minimum LCOE points.

Figure 17 [Figure 17: see original paper] presents the Taylor diagram for evaluating the four decision points. The correlation coefficient (Ccoef), root-mean-squared deviation (Rrmsd), and standard deviation (Sstd) are represented by blue dashed lines, green dashed lines, and black arcs, respectively. For example, the TOPSIS point for RC in the SFR system has Ccoef = 0.9596, Rrmsd = 0.0093, and Sstd = 0.0094, while the ideal point values are 1, 0, and 0.0179, respectively. The ideal point in the Taylor diagram represents maximum Wnet, t, e, and IRR, and minimum LCOE, Ctot, SC, APR, and SP—a different interpretation from the Pareto optimal frontier.

Decision points are selected based on the principle that smaller Rrmsd and Ccoef absolute values closer to 1 indicate proximity to the ideal point. The Shannon entropy point consistently remains far from the ideal point, indicating that single-objective optimal results (maximum t) should not be selected as optimized working conditions. In the SFR-RC system, the ideal, Shannon entropy, LINMAP, TOPSIS, and AHP points have Rrmsd values of 0, 0.0386, 0.0117, 0.0093, and 0.0054; Ccoef values of 1, -0.9648, 0.9682, 0.9596, and 0.9529; and Sstd values of 0.0178, 0.0210, 0.0065, 0.0094, and 0.00170, respectively. Therefore, AHP is determined as the final optimal Pareto solution closest to the ideal point.

Similarly, in the GFR-SR system, the four decision points have Rrmsd values of 0.01376, 0.00417, 0.00512, and 0.0041, with Ccoef values of -0.6512, 0.8969, 0.5718, and 0.8245. The Shannon entropy and TOPSIS points have larger Rrmsd values, while LINMAP and AHP have similar Rrmsd values, but LINMAP's Ccoef is closer to 1. Therefore, the LINMAP point is selected as the optimal point.

Figure 18 [Figure 18: see original paper] summarizes the specific Taylor diagram values for all scenarios.

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4. Optimization Results and Parameter Analysis

Table 13 presents the specific multi-objective optimization results. Notably, the shunt ratio (SR) and primary compression pressure (Pz) concentrate around 50% and 8.0 MPa—the minimum values of their iteration ranges. A smaller SR improves the cycle's narrow point temperature difference, increasing heat transfer efficiency, which enhances net cycle efficiency and reduces power generation costs. Lower primary compression pressure reduces compression energy consumption, thereby improving cycle efficiency. The cycle maximum temperature approaches the iteration maximum, indicating that within a certain range, higher turbine inlet temperatures yield higher net cycle efficiency and lower LCOE.

The optimal cycle maximum pressure (Pmax) is around 20 MPa or 30 MPa, near the upper iteration limit. Higher pressure does not necessarily improve thermodynamic efficiency or reduce power generation costs. RC and RH cycles achieve better thermodynamic and techno-economic performance at lower pressures. Compressor and turbine efficiencies (C and T) range from 84% to 89%, indicating that while higher efficiencies improve cycle performance, they also increase system costs. Appropriate values optimize both thermodynamic and economic performance. Most final decision points fall under AHP, TOPSIS, and LINMAP schemes, while the Shannon entropy method proves unsuitable for optimization decisions.

Tables 14 and 15 provide specific data before and after optimization. Figure 19 [Figure 19: see original paper] shows the percentage change for each index. Comparison reveals significant system performance improvement after NSGA-II optimization, with positive changes indicating increase and negative changes indicating decrease. Net output power (Wnet), net efficiency (t), and exergy efficiency (e) all increase, demonstrating substantial thermodynamic performance improvement. The MSR-IC scheme shows the most pronounced improvement, with the three indices increasing by 8.58%, 8.58%, and 11.21%, respectively.

SC and LCOE decrease while IRR increases, indicating improved overall system economics. However, Ctot also increases because the optimization objectives (t and LCOE) do not simultaneously consider Ctot, and these objectives are mutually constrained. The LFR-SR scheme shows the largest Ctot increase at 27.78%, while its IRR increases by only 7.8%. This optimization improves thermodynamic efficiency and plant revenue but proves unfavorable for capital-constrained investors. Different cycle arrangements show varying SP changes: IC and SR turbine compactness improves by 10%-15%, while RC and RH compactness decreases. SFR-RC compactness decreases by 3.79%, with other changes being insignificant.

5. Comprehensive Multi-Index Evaluation Results

After processing optimized scheme indexes using the G1+TOPSIS method, Figure 20 [Figure 20: see original paper] illustrates the strengths and weaknesses of each index for each scheme. Each colored line represents a reactor-cycle combination, with the enclosed area indicating option superiority. The RC area is largest, indicating RC has the best overall performance among the four cycle layouts, followed by SR and IC, with RH performing worst. SR's C10 index is more prominent while RC's is depressed, indicating RC requires larger heat transfer area per unit net output power, making it less compact. Although RH shows poor performance across all indexes, its C6 index is most prominent, indicating RH requires the lowest initial investment cost. IC's C8 index is more prominent, showing it has the lowest LCOE. Each scheme offers different characteristics for decision-maker selection.

Figure 21 [Figure 21: see original paper] presents the final comprehensive evaluation results. Weights calculated using the G1 method are B1 (0.3972), B2 (0.2482), B3 (0.2069), and B4 (0.1478). The final reactor ranking is MSR > LFR > SFR > GFR, while the cycle layout ranking is RC > SR > IC > RH. For nuclear Brayton cycles, MSR-RC is the best scheme, followed by MSR-SR and GFR-RC, with GFR-SR and GFR-RH showing the worst evaluation results. This ranking reflects the greater importance placed on safety, where MSR performs best. The cycle layout rankings are consistent with previous single-objective analyses.

6. Conclusions

This study developed mathematical models of the Brayton cycle for four different layouts. Parametric analysis investigated seven crucial parameters affecting thermo-economic performance. The NSGA-II method simultaneously optimized maximizing t and minimizing LCOE. Four decision methods obtained compromise schemes from Pareto optimal frontiers, with Taylor diagrams evaluating these solutions to identify optimal schemes. Changes in indexes before and after optimization were analyzed and discussed. The main conclusions are:

1. Higher pressure does not necessarily improve thermodynamic efficiency or reduce power generation costs. RC and RH cycles achieve better thermodynamic and techno-economic performance at lower pressures.
2. Optimization improves the overall performance of nuclear Brayton cycle systems. The MSR-IC scheme shows the most noticeable improvement, with Wnet, t, and e increasing by 8.58%, 8.58%, and 11.21%, respectively.

3. The LFR-SR optimization increases Ctot by 27.78% while IRR increases by only 7.8%, which is unfavorable for capital-constrained investors.
4. Among the four layouts, RC has the best overall performance, followed by SR and IC, with RH performing worst. However, RH has the lowest Ctot, and IC has the lowest LCOE.
5. Considering all indexes across four levels, the final reactor ranking is MSR > LFR > SFR > GFR, and the cycle layout ranking is RC > SR > IC > RH. For nuclear Brayton cycles, MSR-RC should be prioritized, while GFR-RH should be considered carefully.

Supercritical fluid power cycles have great application potential. This study's mathematical models and optimization decision methods can guide nuclear power plant design and broader energy fields with potential heat resources.

Appendix A. Nusselt Number and Friction Factor Calculation

For semi-circular straight channel PCHEs, the Nusselt number is calculated using the Gnielinski correlation [44]. The friction factor (f) for the Darcy-Weisbach equation depends on channel relative roughness and Reynolds number. The Reynolds number transition from laminar to turbulent flow is calculated using established correlations. When $Re_1 > Re > Re_2$, f is obtained from Eq. A1, where f_1 is calculated using Idelchik's formula [46]. The Colebrook-White correlation [44] calculates f , with f determined iteratively. When the error between f and f is less than 0.01, f = f is assumed. For more information on these equations, refer to the cited references.

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Author Contributions

All authors contributed to study conception and design. Material preparation, data collection, and analysis were performed by Guopeng Yu, Yongfeng Cheng, Na Zhang, and Pingjian Ming. The first draft was written by Guopeng Yu and Yongfeng Cheng and supervised by Pingjian Ming. All authors commented on previous manuscript versions and approved the final manuscript.

Data Availability Statement

The data supporting this study's findings are openly available in the Science Data Bank at https://cstr.cn/[31253.11.sciencedb.13640] and https://www.doi.org/[10.57760/sciencedb.13640].

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